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Impacts of Grazing on Soil Physical Properties as a Result of Reindeer Herding in Northern Scandinavia (Workpackage 9.1)

Introduction

Animals exert pressures on the soil surface when grazing or trampling leading to an increase in soil stresses. Whether or not a soil body responds to this stress increase with large volumetric and/or shear deformation depends on the "natural" stability or strength of the soil. However, if the stability/strength of the soil is exceeded soil compaction accompanied by a change of soil physical properties will be the result, which may increase the risk for soil erosion and limit plant growth (Greenwood & McKenzie, 2001). Willat & Pullar (1983) showed in an experiment with different stocking densities a decrease in saturated hydraulic conductivity with increasing stocking rate. In other experiments Tanner & Mamaril (1959) and Federer et al. (1961) found that treading animals caused a decrease in air permeability and Gifford & Hawkins (1978) pointed out that animal treading can result in a marked reduction in infiltration. In other words, trampling induced soil deformation changes the functioning of a soil and by that imposes constraints on habitat requirements for plants and micro-organisms.

It has been recognised that grazing/trampling not only involves soil structural changes accompanied by a change in pore-size distribution, which influences soil aeration and hydraulic conductivities. Another important factor is the alteration of soil surface properties in the course of the reduction/degradation of the vegetation cover, particularly the lichen cover, which affects soil temperatures as well as the flow of water and heat and thus controls the soil's water- and energy household.

Focus of WP9.1 was to assess soil stability/strength parameters and to investigate and quantify the effects of grazing activity on soil physical properties as described above at selected sites in boreal forest and tundra environments in Northern Fennoscandia. This research aimed at the evaluation of possible consequences for habitat functioning and the sustainability of the environment both from a soil physical point of view and by correlating results with chemical and microbial soil properties as they have been measured by other workpackages at the same research sites.

Study sites and soils

We investigated a total of 15 soil profiles at two study sites with respect to the impact of grazing and forestry activity, as another form of land use, on soil physical properties: 10 soil profiles at a forest study site Vuotso (68°09'N, 26°36'E) (including a wheeling track of a forestry harvester) and 5 soil profiles at a tundra study site Jauristunturit (68°49'N, 23°48'E). It is difficult to relate the particular sampling sites directly to stocking rates, however, the chosen soil profiles represent a trampling intensity gradient ranging from high trampling intensity (e.g. a trample path or a coral) over moderate trampling intensity at evidently grazed spots to low resp. no trampling intensity at undisturbed reference sites. To further investigate the influence of different management systems on soil physical properties, we have compared summer and winter grazed areas at the Jauristunturit site at the Finnish-Norwegian border. The fence in this area has been relocated approximately 10 years ago so that we can distinguish following management gradient: summer and winter grazed for more than 40 years (Finnish side), summer and winter grazed for ~10 years (Finnish side), only winter grazed (Norwegian side). An overview of the investigated soil profiles and their characteristics as well as their associated trampling intensity and management practice is given in Table 1.

Materials and Methods

To assess soil physical properties of the selected sites undisturbed soil samples have been taken at 2-3 depths. Pore size distributions and saturated hydraulic conductivities have been measured on 4 cm high standard steel cylinders with a diameter of 6 cm. Desorption curves were obtained by means of a tension plate assembly with suctions of -10, -30, -60, -150 and -300 hPa from which pore size distributions have been calculated. Saturated hydraulic conductivities have been measured with the aid of a falling head permeameter. Unsaturated hydraulic conductivity functions $k(\theta)$ were measured using the evaporation method (Plagge, 1991) as well as modelled from the water retention data with the aid of the RETC code (van Genuchten, 1991) applying a van Genuchten - Mualem modelling approach. At some sampling sites horizontal and vertical samples have been taken to investigate anisotropy effects for saturated hydraulic conductivities.

For determining mechanical stability parameters (shear parameters, pre-compression stresses) standard steel cylinders (h = 3 cm, Ø = 10 cm) have been taken. Pre-compression stress values were derived from the compression curves of confined compression tests (oedometer tests) by applying the Casagrande method (Casagrande, 1936). Samples have been pre-treated by applying a suction of -60 hPa to adjust them to the same matric potential. Before and after compression, air permeability has been determined by applying an air pressure (gauge pressure of 1 hPa) and measuring the air flow through the soil sample with the aid of rotameters (FR2000, Key Instruments). Shear parameters (angle of internal friction, cohesion) were obtained by direct shear tests after consolidation. In addition cyclic loading tests have been conducted to investigate the effect of repeated loading, unloading and reloading on soil structural changes. For this homogenised soil of different soil texture has been moulded into the standard steel cylinders with a loading frame to produce different initial soil

Profile-No.	Soil type	Soil-Horizon	Depth [cm]	Soil-Texture	Soil-Fabric	Criteria
VP1-U	**Haplic Podzol**	L	+8			
		O	+6			
Boreal	Parent Mate-	E	4	S	sg	low
forest	rial:	Bs1	20	S	sg	trampling in-
	Till	Bs2	35		sg	tensity
		Bc	50		sg	"ungrazed"
		C	55 +			
VP1-G	**Haplic Podzol**	L/O	+2			
		E	2	LS	pla	moderate
Boreal	Parent Mate-	Bs1	15	LS	sg	trampling in-
forest	rial:	Bs2	30			tensity
	Till	C	40 +			"grazed"
VP1-T	**Haplic Podzol**	L/O	+1			
		E	3	LS	pla	high
Boreal	Parent Mate-	Bs1	13	LS	sg	trampling in-
forest	rial:	Bs2	30	LS		tensity
	Till	C	40 +			"trample path"
VP2-I	**Haplic Podzol**	AE	2		pla	
		E	6	S	pla	high
Boreal	Parent Mate-	Bs1	23	S	pla ...10cm	trampling in-
forest	rial:	Bs2	33	S	sg	tensity
	glazifluvial	C	40 +	S	sg	"coral inside"
	sand					
VP2-II	**Haplic Podzol**	L	+4			
		O	+3.5			low
Boreal	Parent Mate-	E	4	S	sg	trampling in-
forest	rial:	Bs	22	LS	sg	tensity
	glazifluvial	C	40 +	S	sg/lay	"coral outside"
	sand					
VP3-U	**Haplic Podzol**	L	+8			
		O	+2			
Boreal	Parent Mate-	E	2	S	sg	low
forest	rial:	Bs1	10	S	sg	trampling in-
	glazifluvial	Bs2	15	S	sg	tensity
	sand	C	30 +	S	sg/lay	"ungrazed"

Table 1 *Soil types, diagnostic horizons and associated trampling intensity or management practice criteria.*

bulk densities. The samples were adjusted to a reference matric potential of -60 hPa (suction plate), and subsequently repeatedly loaded (30 sec) and unloaded (30 sec) with 40 kPa in an oedometer. The number of cycles varied from 0 (reference) to 1, 2, 3, 5, 10, 20, 50, and 100 cycles.

To investigate the effect of vegetation disturbances by trampling on water infiltration and soil temperature monitoring profiles have been installed at the profiles MP-L, MP-M and MP-H (Table 1) at the tundra study site (Jauristunturit). Volumetric water contents were measured using a newly developed sensor called ECH_2O at three depths. ECH_2O uses the capacitance technique to measure the dielectric permittivity of the surrounding medium, which correlates with the volumetric water content. Soil specific calibration of the sensors has been carried out in the laboratory after their removal from the monitoring sites accounting for the influence of soil textures and soil bulk densities on output signals. Soil temperatures have been recorded using PT-100 temperature sensors at five

Table 1 continued *Soil types, diagnostic horizons and associated trampling intensity or management practice criteria.*

Profile-No.	Soil type	Soil-Horizon	Depth [cm]	Soil-Texture	Soil-Fabric	Criteria
VP3-G Boreal forest	**Haplic Podzol** Parent Material: glazifluvial sand	L/O E Bs C	+0.5 3 17 40 +	 S S S	 sg sg sg/lay	moderate trampling intensity "grazed"
VP3-T Boreal forest	**Haplic Podzol** Parent Material: glazifluvial sand	E Bs C	1 8 30 +	S S S	sg sg sg/lay	high trampling intensity "trample path
VP4-U Boreal forest	**Haplic Podzol** Parent Material: Till	L O E Bs C	+6 +3 5 16 50 +	 LS LS LS	 sg sg sg	 no wheeling track
VP4-F Boreal forest	**Haplic Podzol** Parent Material: Till	AE Bs1 Bs2	10 20 40	SL SL	pla pla	wheeling track
NP-G Tundra	**Haplic Podzol** Parent Material: Till	L/O E Bs C	+4 1 20 25 +	 LS	 sg sg sg	moderate trampling intensity "grazed"
NP-T Tundra	**Haplic Podzol** Parent Material: Till	AE Bs C	2 20 25 +	 LS	sg sg sg	high trampling intensity "trample path"
MP-L Tundra Monitoring Profile	**Haplic Podzol** Parent Material: Till	L O E Bs C	+3 +2.5 4 20 30 +	 LS LS LS	 sg sg sg	only winter grazed undisturbed lichen cover
MP-M Tundra Monitoring Profile	**Haplic Podzol** Parent Material: Till	L O E Bs C	+4 +3.5 3 10 30 +	 LS SL SL	 sg sg sg	summer & winter grazed ~10 years moderately disturbed lichen cover
MP-H Tundra Monitoring Profile	**Haplic Podzol** Parent Material: Till	O AE E Bs C	+2.5 1 4 22 30 +	 LS SL SiL	 sg sg sg	summer & winter grazed >40 years heavily disturbed lichen cover

depths. All measurements have been collected with the aid of Delta T-Loggers at 30 min intervals. Monitoring has been conducted during the vegetation periods in 2002 and 2003.

Results

Saturated hydraulic conductivity

Measurements of saturated hydraulic conductivities (K_{sat}) are summarised in Table 2. Overall saturated hydraulic conductivities are medium to very high, ranging from 10^{-4} to 10^{-2} cm s^{-1}. A decrease in K_{sat} can be observed with increasing trampling intensity at sampling site one (VP1-T, VP1-G, VP1-U) and three (VP3-T, VP3-G, VP3-U). K_{sat}-values at the trampled sites (VP1-T, VP1-G) are about one magnitude lower compared to the undisturbed site VP1-U for both horizontally and vertically orientated samples. The decrease of K_{sat} with increasing trampling intensity at site three (VP3-T, VP3-G, VP3-U) is less pronounced. Although the mean of the log-normalised data (Table 2) show slightly lower vertical compared to horizontal hydraulic conductivities for VP1-T and VP1-G the difference is not significant.

Significant differences of vertical and horizontal K_{sat}-values are observed within the topsoil layers at site three (VP3-T, VP3-G, VP3-U), however, this effect can not be related to trampling since it occurs also at the undisturbed site VP3-U. The lowest saturated hydraulic conductivities have been found at site VP4-F at a depth of ~20-30 cm indicating the rather deep penetration of the deformation zone under wheeling tracks of forestry harvesters. Saturated hydraulic conductivities at this site are higher in the horizontal direction compared to the vertical direction, which corresponds to the field observation of a platy soil structure at this profile. No significant correlation of saturated hydraulic conductivities to grazing/trampling intensity could be found at the Jauristunturit study sites (NP-G, NP-T, MP-L, MP-M and MP-H).

Pore size distribution and unsaturated hydraulic conductivity

Results of pore size distributions (Tab. 3) correspond well to the K_{sat}-measurements. At the sites VP1-T, VP1-G and VP1-U the measurements indicate changes in soil structure with increasing trampling intensity. The total pore volume (TPV) drops from about 60% (VP1-U) to less than 50% (VP1-T, VP1-G), which is related to a decrease of macropores (MaP) while the number of large mesopores (LMP) and small mesopores (SMP) is increasing. This change in soil structure is also clearly reflected by the water retention curves shown in Figure 1. The shapes of the curves reveal compaction effects for the two trampled sites VP1-T and VP1-G. Soil compaction due to trampling goes along with an increase of soil bulk density of nearly 25% at VP1-T and VP1-G compared to VP1-U. Changes in pore size distributions at the sites VP3-T, VP3-G and VP3-U as a result of trampling are minor and soil bulk densities increase only slightly with trampling intensity. Results of the pore size analysis from Jauristunturit study area show differences, but similar to the K_{sat}-measurements no clear relationship with grazing/trampling intensity has been observed.

Table 2 *Saturated hydraulic conductivity measurements (K_{sat}). Confidence limits have been calculated using Student´s t-method; v = vertical orientation, h = horizontal orientation of the sample, n = number of samples, SD = standard deviation, CV = coefficient of variation.*

Site		Direc-tion	Depth [cm]	n	Geom. Mean	Mean	Geom. Mean	SD	CV	95% conf. limits
		v/h	Center of zyl.		Kf [cm/s]	Log-Kf [cm/s]	Kf [cm/d]	Log-Kf [cm/s]	[%]	+/-
VP1-U	Depth 1	v	+4-0	4	1.77E-02	-1.75	1526	0.14	7.9	0.19
		h	-	-	-	-	-	-	-	-
	Depth 2	v	4-8	4	1.11E-02	-1.95	962	0.11	5.6	0.15
		h	5-11	4	1.19E-02	-1.92	1029	0.17	8.7	0.23
VP1-G	Depth 1	v	+1-3	4	4.40E-03	-2.36	380	0.23	9.7	0.32
		h	0-6	4	1.04E-02	-1.98	896	0.29	14.7	0.40
	Depth 2	v	5-9	4	1.48E-03	-2.83	128	0.50	17.6	0.69
		h	6-12	4	1.61E-03	-2.79	140	0.37	13.2	0.51
VP1-T	Depth 1	v	+1-3	4	1.48E-02	-1.83	1283	0.11	6.3	0.16
		h	0-6	4	1.99E-03	-2.70	172	0.31	11.6	0.43
	Depth 2	v	5-9	4	1.25E-03	-2.90	108	0.20	6.7	0.27
		h	6-12	2	1.82E-03	-2.74	158	0.37	13.5	1.12
VP2-I	Depth 1	v	0-4	4	2.46E-03	-2.61	212	0.12	4.5	0.16
		h	-	-	-	-	-	-	-	-
	Depth 2	v	6-10	4	5.57E-03	-2.25	481	0.06	2.8	0.09
		h	7-13	4	8.23E-03	-2.08	711	0.12	5.7	0.17
VP2-II	Depth 1	v	+2-2	4	8.59E-03	-2.07	742	0.07	3.4	0.10
		h	-	-	-	-	-	-	-	-
	Depth 2	v	6-10	4	3.79E-03	-2.42	327	0.08	3.3	0.11
		h	7-13	4	4.72E-03	-2.33	408	0.13	5.6	0.18
VP3-U	Depth 1	v	2-6	5	1.42E-02	-1.85	1226	0.04	2.3	0.05
		h	2-8	5	2.29E-02	-1.64	1975	0.10	5.9	0.11
	Depth 2	v	8-12	5	1.94E-02	-1.71	1672	0.04	2.3	0.05
		h	-	-	-	-	-	-	-	-
	Depth 3	v	13-17	5	1.66E-02	-1.78	1432	0.04	2.4	0.05
		h	12-18	5	1.98E-02	-1.70	1715	0.04	2.1	0.04
VP3-G	Depth 1	v	0-4	5	8.63E-03	-2.06	746	0.07	3.2	0.08
		h	1-7	5	1.43E-02	-1.84	1236	0.08	4.1	0.09

Unsaturated hydraulic conductivity functions for the sites VP1-T, VP1-G and VP1-U are shown in Figure 2. At matric potentials above pF 1.8 hydraulic conductivities are higher for the untrampled site VP1-U compared to the two trampled sites VP1-T and VP1-G. As matric potentials are decreasing a drop of the hydraulic conductivity for all sites can be noticed being steepest for the untrampled site VP3-U. However, at matric potentials below pF 1.8 hydraulic conductivities are now even lower for the untrampled site VP1-U compared to the trampled sites VP1-T and VP1-G with differences progressively increasing with decreasing matric potential.

Table 2 continued

Site		Direction	Depth [cm]	n	Geom. Mean	Mean	Geom. Mean	SD	CV	95% conf. limits
		v/h	Center of zyl.		Kf [cm/s]	Log-Kf [cm/s]	Kf [cm/d]	Log-Kf [cm/s]	[%]	+/-
	Depth 2	v	5-9	5	1.45E-02	-1.84	1253	0.03	1.5	0.03
		h	-	-	-	-	-	-	-	-
	Depth 3	v	10-14	5	1.15E-02	-1.94	995	0.06	3.2	0.07
		h	10-16	5	1.31E-02	-1.88	1134	0.05	2.6	0.06
VP3-T	Depth 1	v	0-4	5	9.29E-03	-2.03	803	0.05	2.7	0.06
		h	1-7	5	1.67E-02	-1.78	1444	0.15	8.2	0.17
	Depth 2	v	6-10	5	1.35E-02	-1.87	1170	0.04	2.0	0.04
		h	-	-	-	-	-	-	-	-
	Depth 3	v	12-16	5	1.14E-02	-1.94	987	0.05	2.4	0.05
		h	10-16	5	1.14E-02	-1.94	983	0.02	0.8	0.02
VP4-F	Depth 1	v	7-11	5	2.39E-03	-2.62	206	0.65	24.7	0.74
		h	-	-	-	-	-	-	-	-
	Depth 2	v	15-19	5	2.46E-04	-3.61	21	0.55	15.2	0.63
		h	15-21	5	9.55E-04	-3.02	82	0.27	8.8	0.31
	Depth 3	v	23-27	5	1.36E-04	-3.87	12	0.58	14.9	0.66
		h	23-29	5	6.24E-04	-3.20	54	0.46	14.4	0.53
NP-G	Depth 1	v	3-7	5	4.22E-03	-2.37	365	0.31	13.1	0.36
	Depth 2	v	9-13	5	1.44E-03	-2.84	124	0.14	5.1	0.17
NP-T	Depth 1	v	3-7	5	3.75E-03	-2.43	324	0.22	9.1	0.25
	Depth 2	v	9-13	5	1.98E-03	-2.70	171	0.14	5.1	0.16
MP-L	Depth 1	v	3-7	5	2.71E-03	-2.57	234	0.81	31.5	0.93
	Depth 2	v	10-14	5	2.13E-03	-2.67	184	0.22	8.1	0.25
MP-M	Depth 1	v	1-5	5	6.92E-03	-2.16	598	0.26	12.1	0.30
	Depth 2	v	8-12	5	7.68E-04	-3.11	66	0.47	15.1	0.54
MP-H	Depth 1	v	3-7	5	1.99E-03	-2.70	172	0.22	8.1	0.25
	Depth 2	v	9-13	5	1.56E-03	-2.81	135	0.25	8.7	0.28

Mechanical stability

Measurements of the pre-compression stresses describing the stability of the investigated soils to resist stress increases by trampling animals or forestry equipment are shown in Figure 3. The values range in general from 40 to 70 kPa, except for the sites VP2-I and VP2-II with values of up to 120 kPa. However, the results indicate very low mechanical stabilities for the most soil profiles under investigation. At site one there is no difference in pre-compression stresses between the grazed and ungrazed site although the soil bulk density for the grazed profile VP1-G is significantly higher compared to the ungrazed profile VP1-U (Tab. 3). The same is true when comparing the grazed profile VP1-G with a profile under a wheeling track of a forestry harvester (VP4-F), which reveals even higher soil bulk densities but the same pre-compression stress as VP1-G. Also note that

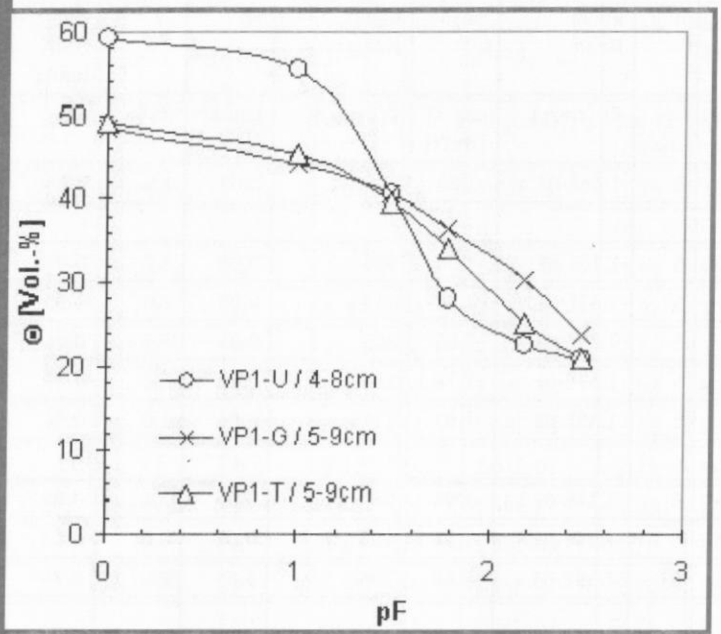

Figure 1 *Water retention curve of site VP1 indicating changes in soil structure as a result of trampling.*

at profile VP4-F the pre-compression stress decreases with increasing soil depth, while the soil bulk density noticeably increases at the same time (Tab. 3).

At site three pre-compression stresses within the topsoil layer are higher at the undisturbed profile (VP3-U) compared to the grazed profile (VP3-G) and the trample path (VP3-T) respectively. Further, VP3-U and VP3-G both seem to have a more uniform distribution of the pre-compression stresses with soil depth as the heavily trampled soil profile (VP3-T) with maximum pre-compression stresses at a depth of 6-9 cm. Pre-compression stresses at the tundra site are also

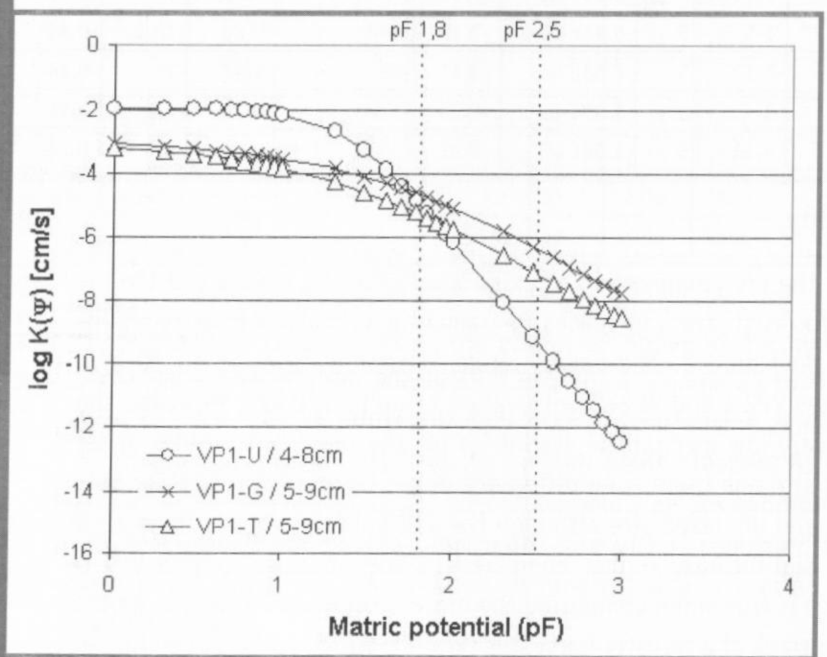

Figure 2 *Unsaturated hydraulic conductivity functions of site VP1.*

Site		Depth	dB	TPV	e	MP1	LMP	SMP	FP	MP2	LMP	SMP	FP
		[cm]	[g/cm3]	[%]	[-]	> 50 mm	10-50 mm	< 10 mm	< 0.2 mm	> 50 mm	10-50 mm	< 10 mm	< 0.2 mm
VP1-T	Depth 1	+1-3	0.60	74.5	2.9	34.0	14.2	26.3		45.6	19.1	35.3	
	Depth 2	5-9	1.35	49.2	1.0	15.2	13.1	20.9		30.9	26.7	42.4	
VP1-G	Depth 1	+1-3	1.02	56.3	1.3	9.3	14.5	32.5		16.6	25.7	57.7	
	Depth 2	5-9	1.36	48.5	0.9	12.0	12.6	13.7	10.1	24.8	26.1	28.3	20.9
VP1-U	Depth 1	+4-0	0.15	89.1	8.2	59.9	4.7	24.5		67.2	5.3	27.5	
	Depth 2	4-8	1.08	59.3	1.5	31.1	7.2	12.6	8.3	52.5	12.1	21.3	14.1
VP2-I	Depth 1	0-4	0.96	63.7	1.8	27.4	5.7	22.8	7.9	43.0	8.9	35.8	12.3
	Depth 2	6-10	1.16	56.3	1.3	30.3	8.2	10.8	7.1	53.8	14.5	19.2	12.5
VP2-II	Depth 1	+2-2	0.81	59.6	1.5	10.1	23.9	25.7		16.9	40.1	43.0	
	Depth 2	6-10	1.21	54.3	1.2	5.1	24.9	17.6	6.7	9.4	45.9	32.4	12.3
VP3-U	Depth 1	2-6	1.39	47.6	0.9	31.2	3.6	9.8	3.0	65.5	7.6	20.6	6.2
	Depth 2	8-12	1.36	48.6	0.9	36.3	2.8	4.6	4.9	74.6	5.8	9.4	10.1
	Depth 3	13-17	1.53	42.2	0.7	31.8	4.3	0.5	5.7	75.3	10.1	1.2	13.5
VP3-G	Depth 1	0-4	1.34	49.6	1.0	29.2	11.0	6.7	2.7	58.8	22.2	13.4	5.5
	Depth 2	5-9	1.40	47.1	0.9	30.2	8.4	3.3	5.3	64.0	17.8	7.0	11.2
	Depth 3	10-14	1.43	46.1	0.9	30.6	8.0	2.1	5.4	66.5	17.4	4.5	11.7
VP3-T	Depth 1	0-4	1.44	45.8	0.8	27.3	5.3	6.0	7.2	59.7	11.5	13.0	15.8
	Depth 2	6-10	1.49	43.6	0.8	31.0	4.0	2.3	6.3	71.1	9.2	5.2	14.5
	Depth 3	12-16	1.51	43.2	0.8	31.6	4.4	2.0	5.3	73.1	10.1	4.6	12.2
VP4-U		40-44	1.60	39.7	0.7	13.6	8.5	9.8	7.8	34.2	21.5	24.6	19.6
VP4-F	Depth 1	7-12	1.51	43.1	0.8	12.3	1.8	18.2	10.8	28.5	4.3	42.2	25.0
	Depth 2	15-19	1.69	36.3	0.6	7.7	4.5	12.5	11.6	21.3	12.5	34.3	31.9
	Depth 3	23-27	1.76	33.6	0.5	6.6	4.9	9.2	13.0	19.5	14.5	27.3	38.7
NP-G	Depth 1	3-7	1.49	43.7	0.8	16.2	14.9	6.6	6.1	37.0	34.1	15.0	13.9
	Depth 2	9-13	1.52	42.8	0.7	18.8	11.2	7.1	5.6	44.1	26.2	16.6	13.1
NP-T	Depth 1	3-7	1.52	42.5	0.7	16.8	14.3	5.2	6.2	39.4	33.7	12.2	14.6
	Depth 2	9-13	1.51	42.8	0.7	18.0	11.8	7.2	5.8	42.0	27.6	16.9	13.6
MP-L	Depth 1	3-7	1.50	43.2	0.8	19.6	12.3	7.7	3.6	45.3	28.5	17.8	8.4
	Depth 2	10-14	1.41	47.0	0.9	23.9	13.2	5.2	4.7	50.8	28.1	11.0	10.1
MP-M	Depth 1	1-5	1.36	48.5	0.9	26.9	8.6	8.9	4.1	55.5	17.7	18.4	8.4
	Depth 2	8-12	1.50	43.3	0.8	21.2	8.1	9.5	4.6	48.9	18.7	21.9	10.5
MP-H	Depth 1	3-7	1.64	38.0	0.6	19.7	7.4	8.0	2.9	52.0	19.4	21.0	7.6
	Depth 2	9-13	1.62	38.7	0.6	17.4	7.6	10.0	3.6	45.0	19.7	25.8	9.4

Table 3 *Pore size distribution.*
TPV = total pore volume,
MaP = macropores,
LMP = large mesopores,
SMP = small mesopores,
MiP = micropores,
e = pore number,
dB = soil bulk density,
MP1 = Percentage Sample Volume,
MP2 = Percentage Total Pore Volume.

very low indicating low mechanical stabilities of the soil, however, no clear relationship to management practice (winter versus winter and summer grazing) is evident. Investigations of soil bulk densities along transects perpendicular to the border fence also show no distinct difference between summer and winter ranges (data not shown).

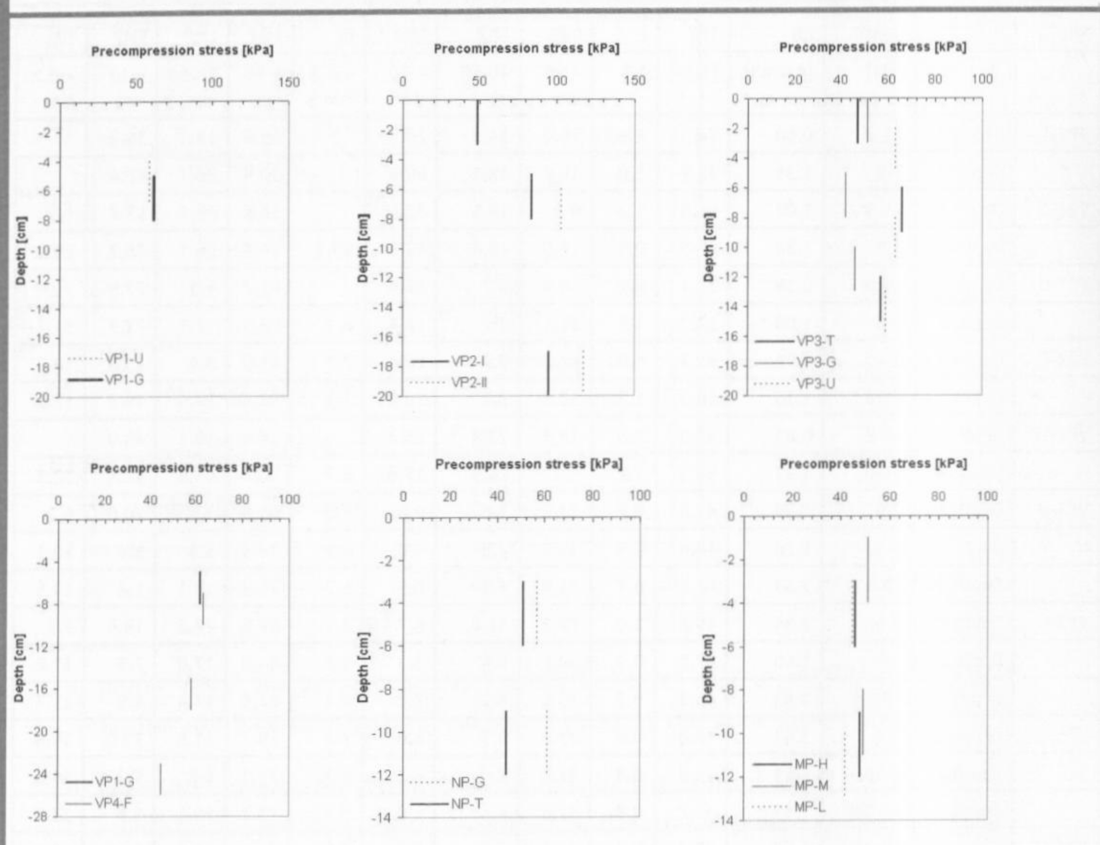

Figure 3 *Pre-compression stresses for the investigated soil profiles.*

Soil water and soil temperature

In contrast, the infiltration of water at the sites with strongly disturbed lichen cover at the >40 years summer and winter grazed area (MP-H) is significantly reduced in comparison to the winter grazed area (MP-L) with undisturbed lichen cover indicated by the volumetric water contents measured at the monitoring profiles. Figure 4 shows the typical increase of soil water content after a rainfall event for the sites MP-H and MP-L respectively clearly displaying the difference in infiltration behaviour. Note that the increase of soil moisture as a result of infiltrating water is delayed by ca. 30 min at the site with undisturbed lichen cover (MP-L). However, once infiltration has started the increase in volumetric water content is rather steep and maximum water contents are approximately 2 Vol.-% higher for the undisturbed lichen cover (MP-L) compared to the strongly disturbed lichen cover (MP-H). Differences in volumetric water content prevail for 2-3 days until field capacity has readjusted.

Also soil temperatures are influenced by changes in lichen cover. Typical soil temperature profiles recorded at solar noon and at midnight for the sites MP-L and MP-H are shown in Fig. 5. Note that soil temperatures within the intact lichen cover (MP-L in Fig. 5) are relatively high at day and very low at night respectively. However, the heat is obviously not conducted to the underlying organic layer during daytime, this is the case where the lichen cover is heavily

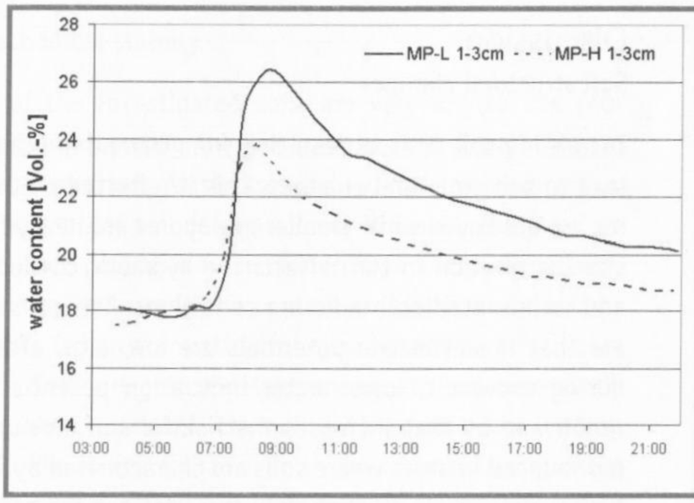

Figure 4 *Volumetric soil water contents after a rainfall event at monitoring sites with undisturbed (MP-L) and heavily disturbed (MP-H) lichen cover.*

disturbed (MP-H). This results in lower soil temperatures at all soil depths where the lichen cover is undisturbed (MP-L) compared to the heavily disturbed lichen cover (MP-H). At night the situation is reverted, i. e., less heat is conducted to the ground surface where the lichen cover is undisturbed (MP-L) indicated by lower differences between night and day temperatures for MP-L compared to MP-H (Fig. 5). Above described effects prevail for the course of the vegetation period leading to an approximately 2-3°C cooler but more balanced temperature pattern where the soil is covered with intact lichens as is shown for the organic topsoil layer in Figure 6.

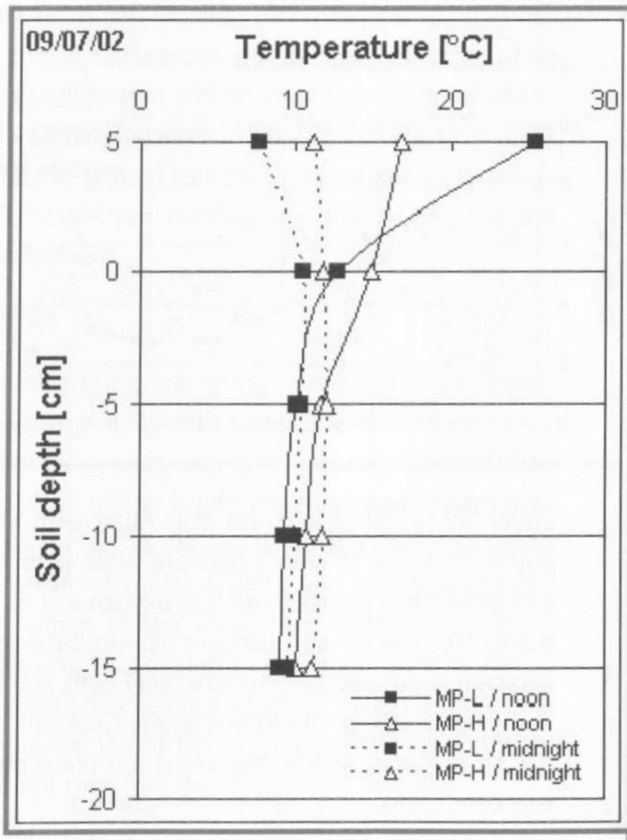

Figure 5 *Soil temperature profiles at monitoring sites with undisturbed (MP-L) and disturbed (MP-H) lichen cover.*

Discussion

Soil structural changes

Increasing soil stresses resulting from trampling reindeer or forestry equipment lead to soil structural changes. This is reflected by the fact that larger mesopores are destroyed while smaller mesopores are newly formed. The change in pore size distribution in turn affects the hydraulic conductivities both for saturated and unsaturated soil moisture conditions. The consequences arising from that are that if soil matric potentials are low, e.g., after heavy rainfall events or during snowmelt, lower water infiltration potentially increases surface water runoff and by that increases the risk for soil erosion. This effect will be most pronounced in areas where soils are characterised by fine soil textures, i. e., with higher clay fraction, which, however, was not the case at the investigated sites. On the other hand, water transport within the soil at higher matric potentials is enhanced by trampling due to the higher fraction of smaller pores, which

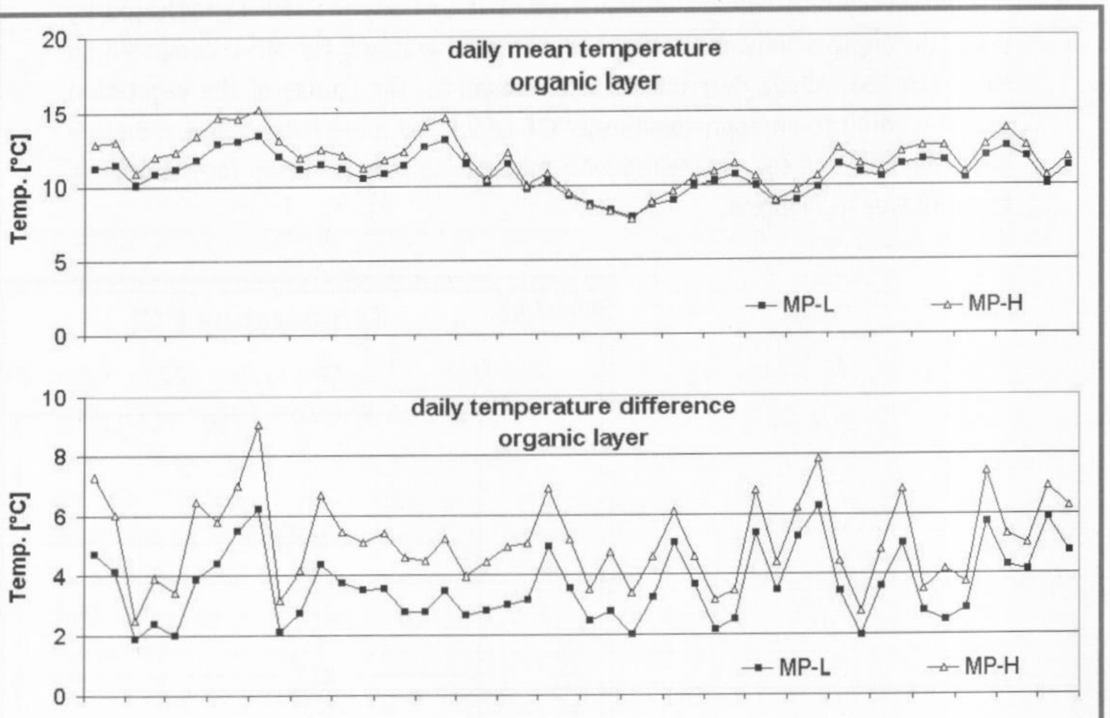

Figure 6 *Soil temperatures and daily temperature fluctuations during the vegetation period 2002 measured in the organic layer at only winter grazed (MP-L) and winter & summer grazed (MP-H) areas.*

under these conditions are still filled with water and thus available as flow paths. However, if more pores are filled with water at a given matric potential soil aeration is reduced and less oxygen will be supplied to micro-organisms and plants. For coarser soil textures as encountered at site VP3 this decrease in soil aeration is not assumed to adversely limit plant growth, however, at sites VP1-G and particularly at site VP4-F, where finer soil textures prevail, air capacities are low to medium, which may constrain plant development, especially under wet soil conditions.

Mechanical stresses and mechanical stabilty

The mechanical stabilities of the investigated soils are very low to low (40-70 kPa). Note that soil stresses exceeding the pre-compression stress will lead to irreversible plastic soil deformation. At stresses below the pre-compression stress usually only elastic (reversible) soil deformation is assumed. However, we calculated static ground contact pressures for reindeer from the average body weight of female animals and by measuring the contact area of hoof indents to an approximate value of 40 kPa (when accounting for dynamic stresses this value might be somewhat higher). Soils are just resistant enough to not excessively undergo plastic deformation when reindeer is trampling. However, cyclic loading test with an axial load of 40 kPa indicate that even if pre-compression stresses are not exceeded small incremental plastic soil deformation takes place (data not shown). The higher the number of cycles the higher the soil deformation, which means that at increasing trampling frequency soil structure will progressively change. This effect is particular visible within trample paths where high numbers of loading, unloading and reloading sequences lead to ever increasing soil deformation.

The inherent risk in this process is that as a result of the reduced saturated hydraulic conductivity and the formation of a channel like micro-topography by bulging up soil material next to the zone of compression, surface water runoff may be accumulated within the trample path after heavy rainfall events or during thaw and thus lead to instantaneous soil erosion. Nevertheless, the low soil stabilities underline the serious consequences one has to bear in mind when loading the soil with heavy forestry equipment whose ground contact pressures (>80 kPa) certainly exceed soil stabilities. Moreover, shearing deformation while machines transfer traction forces on the ground lead to a process known as puddling or kneading, which further decreases soil stability and thus leaves the soil even more susceptible to soil deformation.

Changes in soil surface characteristics

Apart from the mechanical effects of grazing/trampling on soil structure, changes in the vegetation pattern/cover, especially with respect to the lichen cover, resulting from trampling during summer grazing clearly influences water infiltration and soil temperatures. A total lack of the lichen cover at the tundra study site has shown to increase soil temperatures by 2-3°C during the vegetation period. This is assumed to increase soil microbial activity and consequently the decomposition of organic matter, which in the short term enhances nutrient availability but in the long run may lead to a depletion of the nutrient reservoir. Besides the changes in decomposition and chemical reaction rates the lack of a protecting lichen cover promotes the erosion of the organic topsoil layer further increasing the export of nutrients and therefore decreasing soil fertility.

Conclusions

It has been shown that soil structural changes are evidently related to grazing intensity but in comparison to the impacts of forestry machinery the changes caused by trampling reindeer are less pronounced. Working with forestry equipment especially during wet soil conditions seriously damages soil structure and by that deteriorates the physical properties and functions of the soil. However, also a high number of reindeer leading to an increased trampling frequency inevitably result in unfavourable soil deformation making the soil susceptible to soil erosion processes particularly along trample paths. Further, it has been found that summer grazing in the mountainous tundra changes vegetation patterns to the disadvantage of the soil water and temperature household. Therefore, a total destruction of the lichen cover should be avoided and extensively summer grazed areas should be given time to recover until the lichen cover has regenerated.

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